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TECHNICAL MEMORANDUM

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OPTICAL DESIGN FOR AN ARRAY SCANNING BOLOMETER RADIOMETER

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SUMMARY

An optical design is presented for a scanning radiometer which employs as the sensing element a linear array of bolometers. The particular features of the design are that the scanning is accomplished by tilting one of the two optical components and the aberration correction for the window of the bolometer cell is provided by the aspheric surfaces. Tolerances are provided for the various component parameters.

This memorandum serves not only to describe the particular system but also to illustrate the design methods and accuracies available with relatively simply manufactured aspheric surfaces.

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1. BACKGROUND AND REQUIREMENT

The performance of infrared detectors increases with decreasing electrical bandwidth of the output signal and therefore the use of multi-element arrays of detectors can provide better performance than a single detector by allowing the bandwidth of each element to be reduced.

The application under consideration in this memorandum requires that infrared radiation from a field of view 75 mrad (4.3°) vertical by 1.0 mrad horizontal, and with resolutions of 0.5 and 1.0 mrad in the vertical and horizontal directions respectively, be detected with a frequency of 100 Hz. For a single detector a bandwidth of around 15 KHz would be required, but if 20 detectors are used this bandwidth can be reduced 20 times and the amplitude of the scan may be also reduced by suitably spacing the detectors. Such a reduction in bandwidth makes it feasible to employ bolometers as the detectors with their relatively long time constant of about a millisecond.

A requirement of the radiometer for this application is that it be small and inexpensive to produce. It follows that optically it should have only a few easily produced components and that the scanning should be accomplished, if possible, without the introduction of additional components.

The use of uncooled bolometer detectors is in line with the requirement for system simplicity. It must be noted that the spectral response of the bolometers is independent of wavelength over a wide band but in use with near ambient temperature target sources most of the effective radiation will be in the 8 to 14 μm region.

The required optical system parameters are listed in Table 1.

TABLE 1. OPTICAL SYSTEM REQUIREMENTS

1. Optical system	
Aperture	100 mm
Effective focal length	100 mm
Effective T/No.	1.3
2. Focal plane array	
Number of detectors	20
Size	0.05 mm x 0.10 mm
Separation	0.375 mm
3. Vertical scan	
Frequency	100 Hz
Amplitude	0.375 mm (Total)
Total effective array length	7.5 mm
Total effective number of vertical elements	150
Total vertical field	75 mrad (4.3°)

2. OPTICAL DESIGN

2.1 General

Considering the requirement for the images of point objects to be less than 0.5 mrad it is obvious that a single spherical mirror (image extent* 10 mrad for F/1.0) or a parabola (image extent 3 mrad for F/1.0 at 2.3° field of view) are both inadequate. Two-mirror systems were then investigated to see if a suitable optical arrangement could be found that had sufficiently small image extents. The systems investigated were the aplanatic systems of the Cassegrain type. (see figure 1). A number of such systems were designed as described in reference 1 and off axis image extents were calculated by ray tracing for the required field of view and focal ratio. Minimum extents were found for the condition A = 2B (see figure 1), that is when the focus lies half way between the primary and secondary mirrors. Also the minimum decreased with increasing values of A and B.

For a system with an F/number of 1.0 the diameter of the secondary must be nearly equal to B, therefore B cannot be too large if the amount of obscuration is to be realistic. Choosing B as 50 mm and with the focal length 100 mm as specified the image extent was found to vary with A as shown below in Table 2.

TABLE 2. MAXIMUM POINT IMAGE EXTENT*

Distance A (mm)	Maximum point image extent (milliradians)
46	1.8
51	1.7
56	1.6
76	1.1
102	0.6
127	0.8

* Throughout this paper the term image extent indicates the full size of the aberrated image of a point source. The distribution of radiation within this extent will usually make the image effectively smaller. Diffraction effects are about 0.1 mrad and have been ignored.

It was decided to choose the system with A equal to 76 mm for further investiagation and refinement. This choice was based upon the reasoning that firstly, Table 2 shows only the maximum image extents and it is possible that with refinement the extents can be reduced where necessary to meet the requirement. Secondly, the requirement to keep the radiometer small makes it desirable to have the distance between the primary mirror and the focal plane (A-B) as short as possible.

2.2 Optical design congruences

As mentioned in the previous section the aspheric surfaces were designed

as described in reference 1, where Appendix IV provides as an example, the method of congruences applied to the bolometer radiometer. Those congruences were used to design systems for the initial investigations (Section 2.1), but for the final design it was necessary to recalculate the aspheric surfaces so they would correct the aberrations of the window of the bolometer array.

The original congruences were as follows,
for object space,

$$\omega = 0 \qquad h = t \tag{1}$$

and for image space

$$\omega' = -\theta \qquad h' = (XF - X3)\tan\theta \tag{2}$$

The inclusion of the window (see figure 2) modifies only the image space congruence to

$$\omega' = -\theta \qquad h' = (XF - X3 - DD)\tan\theta + DD\frac{\sin\theta}{(n^2 - \sin^2\theta)^{\frac{1}{2}}} \tag{3}$$

where DD is the thickness of the window and n is the refractive index of the window material.

The resulting simultaneous differential equations then become

$$\frac{dx}{dt} = \left[\frac{R - R_x}{R_y}\right]^{-1} \tag{4a}$$

$$\frac{dx'}{dt} = \left[\frac{R\cos\omega' - R_x}{R\sin\omega' - R_y} + \tan\omega'\right]^{-1}\left[\frac{(XF - X3 - DD - X')}{f\cos^3\omega'} + \frac{DD\,n^2}{f(n^2 - \sin^2\omega')^{3/2}}\right] \tag{4b}$$

where f is the focal length

$$R_y = y' - y,\ R_x = x' - x \text{ and } R = (R_x^2 + R_y^2)^{\frac{1}{2}}$$

Solving the two equations (4) provides the meridional curves for the two centro-symmetric aspheric surfaces. These are in cartesian co-ordinate form (600 points for each curve) suitable for input to the ray tracing evaluation computer program and for input to the numerically controlled diamond point cutting lathe which produces the surfaces.

3. COMPUTER EVALUATION OF OPTICAL DESIGN

3.1 Image extents

Using a ray trace program the design was evaluated by assessing the image sizes in the focal plane over the full field of view required (2.3° half field angle). The directions are defined in figure 3(a). These extents are plotted as a function of field angle as the full curves in figure 4 in both the sagittal and tangential directions.

The image extents vary from zero on the optical axis, (as would be expected in an aplanatic system) to 0.25 mrad at the edge of the field in the tangential direction and 1.10 mrad in the sagittal direction. The requirement calls for a resolution of better than 0.5 mrad in the direction along the array which is in the direction of the sagittal extent. However, extents can in general be modified slightly by varying the focal position and this is shown later in Section 3.3. Before doing this the effect on the image extents of nodding the secondary mirror is investigated.

3.2 Image extents when secondary mirror nodded

It is obvious that by nodding either of the mirrors the image will be scanned across the detectors in the focal plane thus providing a convenient method of scanning the array of detectors. This method avoids the introduction of a separate plane mirror for scanning but will, in general, increase the aberrations. To evaluate this increase in aberration, ray traces were carried out with the secondary mirror tilted to assess the image extents under these conditions. For the bolometer radiometer, tilting or nodding is required to shift the image along the length of the linear array. This is referred to here as Z axis nodding. (see figure 3(b)). Nodding about the perpendicular axis, Y axis nodding, was also investigated but this was for reasons of general interest and does not apply to the bolometer systems.

The image extents for the Z axis nodding are shown in figure 4 where two sets of dotted curves are given for nods of the secondary mirror of amplitude 0.5 and 5 mrad. When the secondary mirror nods, as it passes through its central position the image extents lie on the full curves and then the extents generally increase until they lie on a dotted curve at the maximum amplitude of the nod, then decreasing as the mirror returns to its central position followed by an increase to the other dotted curve of the pair at the other extreme. Because the system is unsymmetrical when tilted the amplitudes differ depending upon whether the image swings away or towards the centre of the field. Note also that in some cases the image extent is decreased by the nodding. Similar curves are given for the Y axis nod in figure 5 but these are for completeness and do not apply to the radiometer.

For the radiometer the required amplitude of the nod at the secondary mirror is $\pm 1.85 \times 10^{-3}$ rad and from figure 4 it can be estimated that the image extents will be increased by 0.2 mrad due to this small rotation of the mirror.

3.3 Minimum image extent over the whole field

The image extents discussed in Section 3.1 were for the focal plane (Gaussian focal plane) and in this plane they are zero at the centre of the field. By shifting the image plane away from the Gaussian plane the image sizes can be varied somewhat, and due to a combination of focal surface curvature and astigmatism it is possible to reduce the sagittal extents at the expense of the tangential extents. Being then slightly 'out of focus the on axis extents are non zero'.

It was found that the optimum position was 0.05 mm from the Gaussian focal plane in the direction of the secondary mirror. The extents for this position

are shown in figure 6 together with the limits on the extents for nodding to $\pm 1.85 \times 10^{-3}$ rad. The sagittal extents now vary between 0.11 and 0.60 mrad increasing to 0.78 mrad at the edge of the field during nodding. In the extreme case these are outside the specifications called for, 0.50 mrad, but may be acceptable when considered in relation to the additional complexity required to fully meet the specification. The tangential extents vary from 0.60 to 1.03 mrad and this is considered to satisfy the specification of 1.00 mrad.

4. DEDUCED PARAMETERS AND TOLERANCES

4.1 Stop position

The effect of the position of the aperture stop on the aberrations was investigated and found to be insignificant. It would be most convenient to have the stop physically near the secondary mirror and the following parameters have been calculated on the assumption that the stop and the vertex of the secondary mirror are co-planar.

4.2 Mirror sizes and focal ratios

Primary mirror diameter	112.36 mm
Secondary mirror diameter	66.19 mm
(Stop diameter	101.60 mm)
Optical focal ratio	1.0
Effective T/No. (obscuration only)	1.32

4.3 Secondary mirror rotational axis positional tolerance

Assessments were made on the image extents in Section 3 with the axis of nod 2.5 mm behind the vertex of the secondary mirror. Similar assessments with the axis of nod shifted along the optical axis showed a small but insignificant change to the aberrations over shifts of $\pm$ 3 mm.

4.4 Secondary mirror positional accuracy

The positional accuracy of the secondary mirror, that is the distance between primary and secondary mirrors, is not critical as regards increasing image extents. A tolerance value of $\pm$ 0.025 mm would be appropriate to this spacing but these small changes will be reflected and magnified in the change of focus position. It is assumed that adjustment would be provided for the focus position which will have to be adjusted to $\pm$ 0.0025 mm because of the optical ratio being employed.

5. DISCUSSION OF DESIGN

The design as described above comes close to meeting the requirements but falls short in that the image extents (sagittal) are slightly greater than the 0.5 mm specified and the T/No. is 1.32 rather than 1.30.

While it is considered that this design is adequate methods of improvement are noted. Image extents may be reduced by increasing the distance between the two mirrors ('A' in figure 1). The disadvantage of this are the increased overall size of the system and the consequent weight increase together with an increase in obstruction. (41% with A = 76 mm, 43% with A = 102 mm). Decreasing the optical focal ratio will also improve the image extents. If the focal length is preserved this also reduces the aperture size and to maintain system performance it would be necessary to increase the size of the system by scaling.

The introduction of a third mirror would allow the performance of the system to be improved but this would considerably increase the complexity of the system making the unit more difficult to manufacture and assemble and larger in size.

6. CONCLUSIONS

The optical design presented here is considered to meet the required specifications closely enough to be acceptable. To improve the system would entail penalties of increased size, weight and cost which are less likely to be acceptable than the marginal decrease in performance.

REFERENCES

No.	Author	Title
1	McQuistan, G.W.	"Optical Design of Aspheric Mirrors". WRE Technical Report 1742 (A), March 1977.

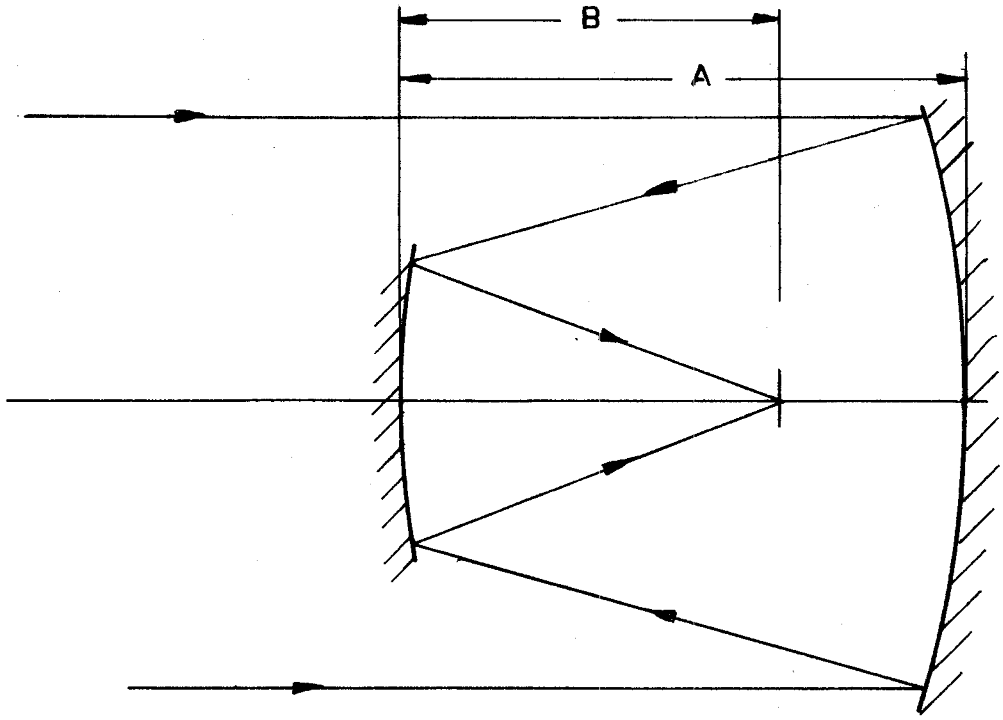

Figure 1. Optical system-schematic

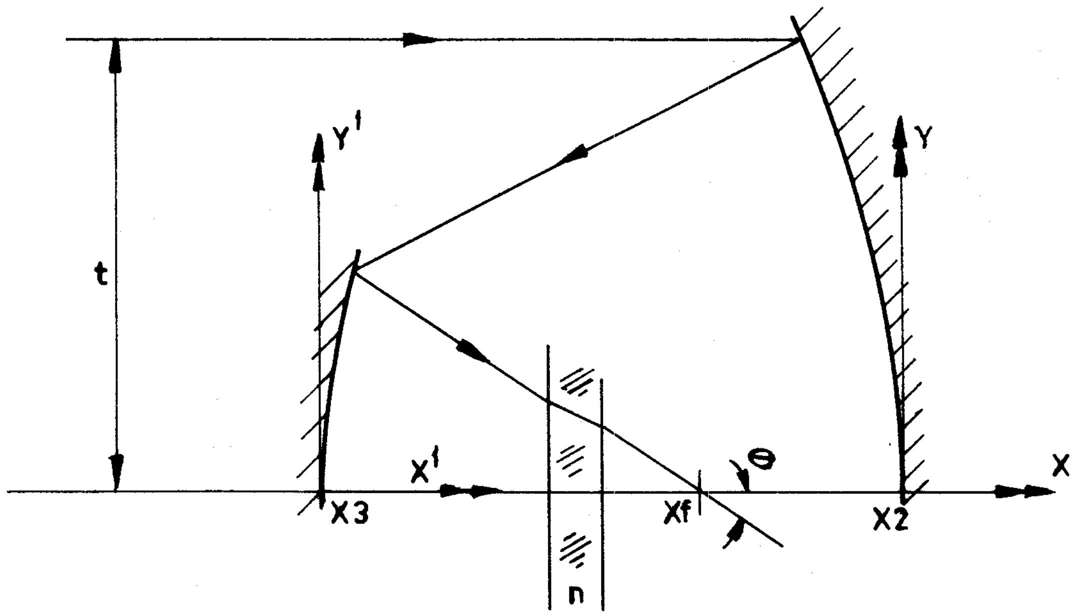

Figure 2. Congruences for bolometer radiometer with window

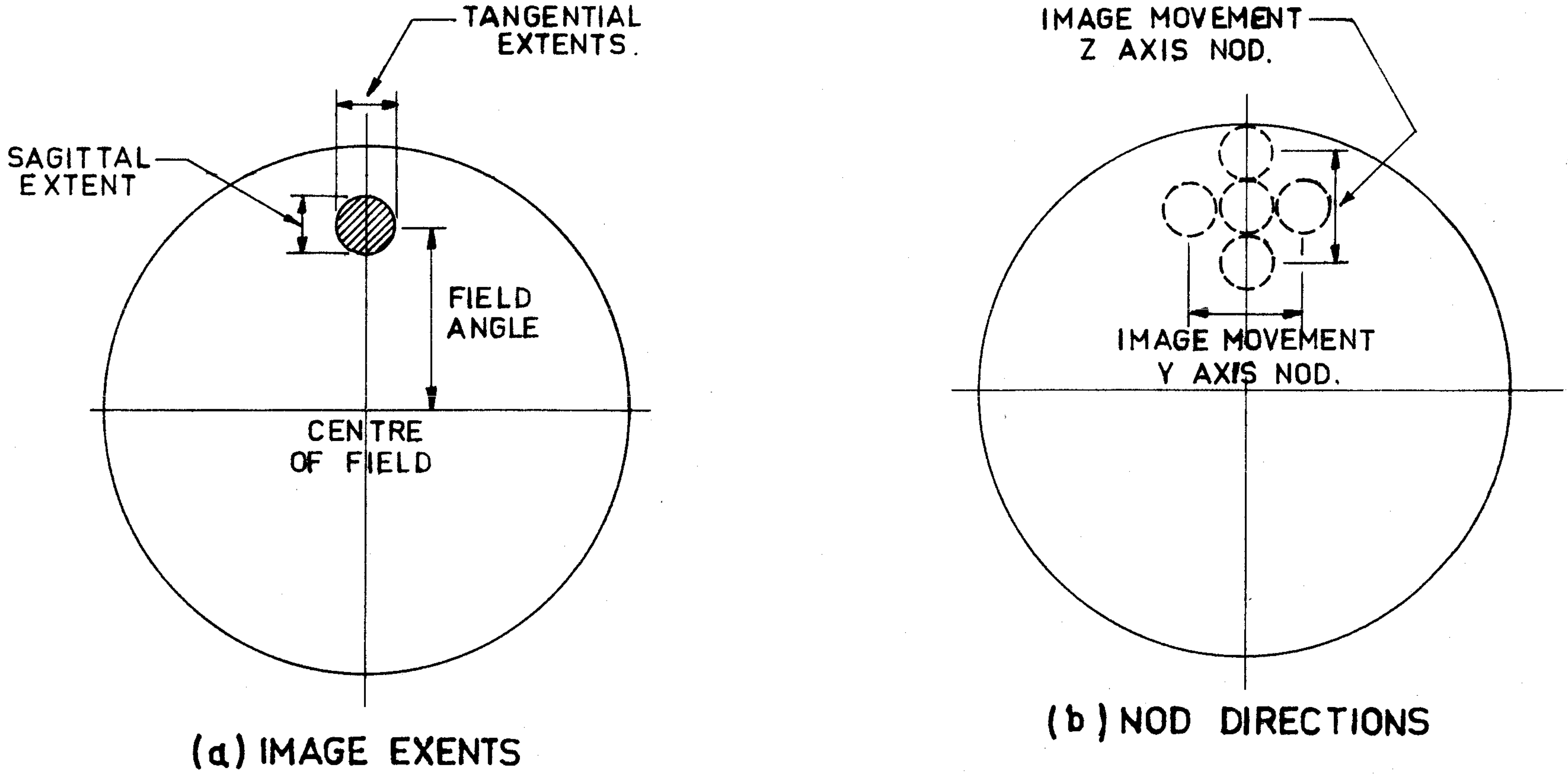

Figure 3. Definitons of image extent directions and nod. directions

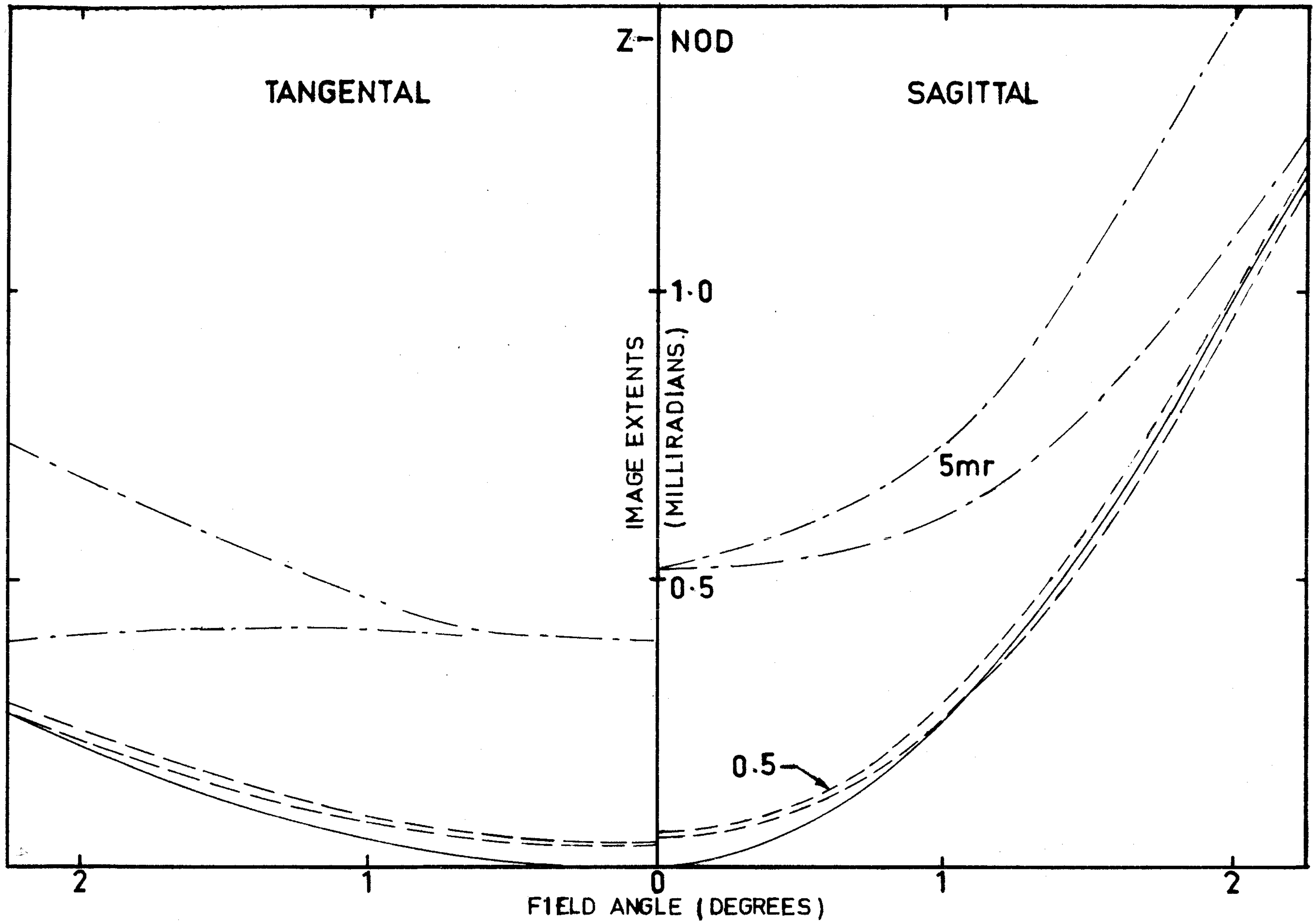

Figure 4. Image extents vs field angle for gaussian focal plane (Z nod)

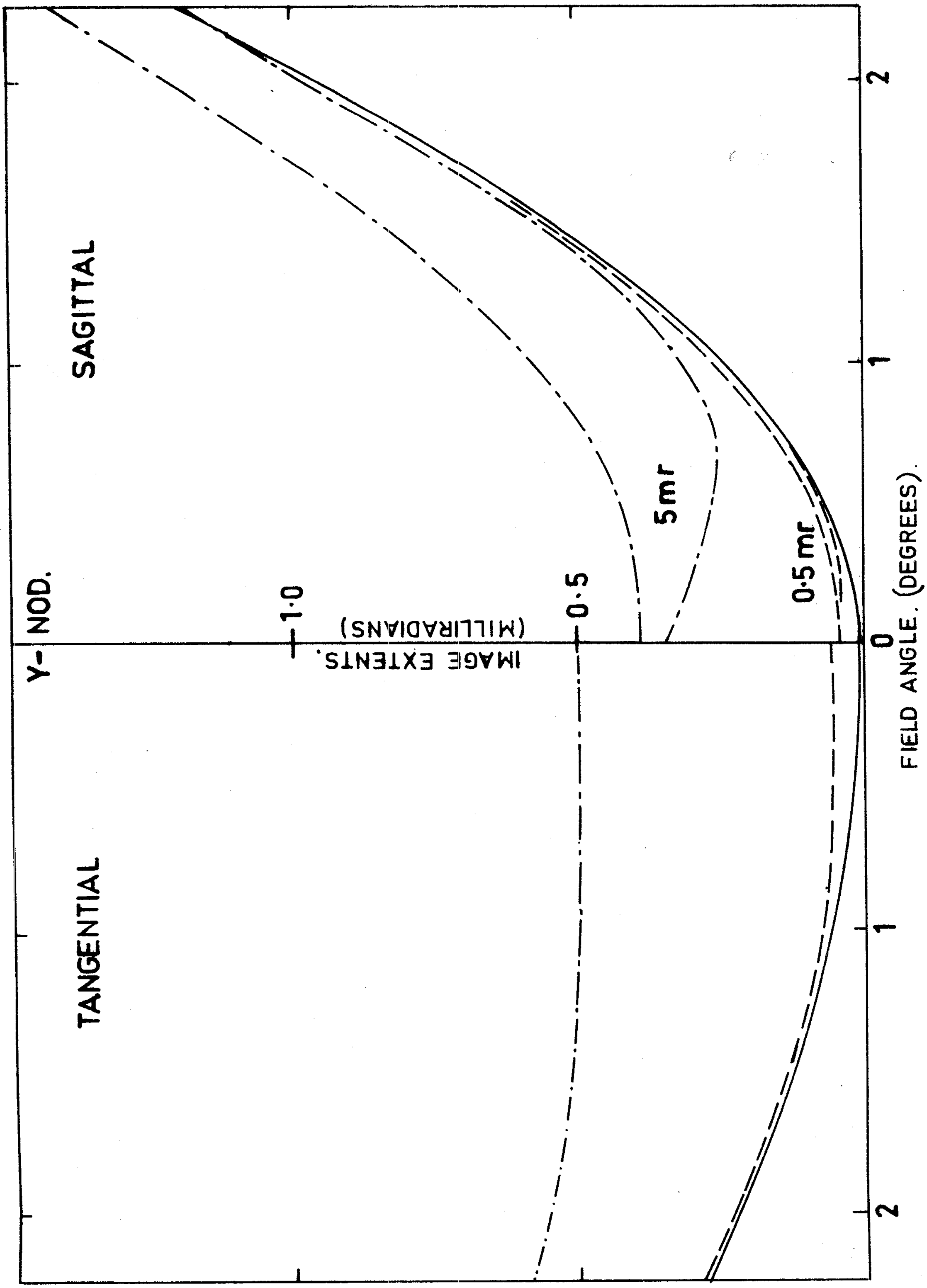

Figure 5. Image extents vs field angle for gaussian focal plane (Y Nod)

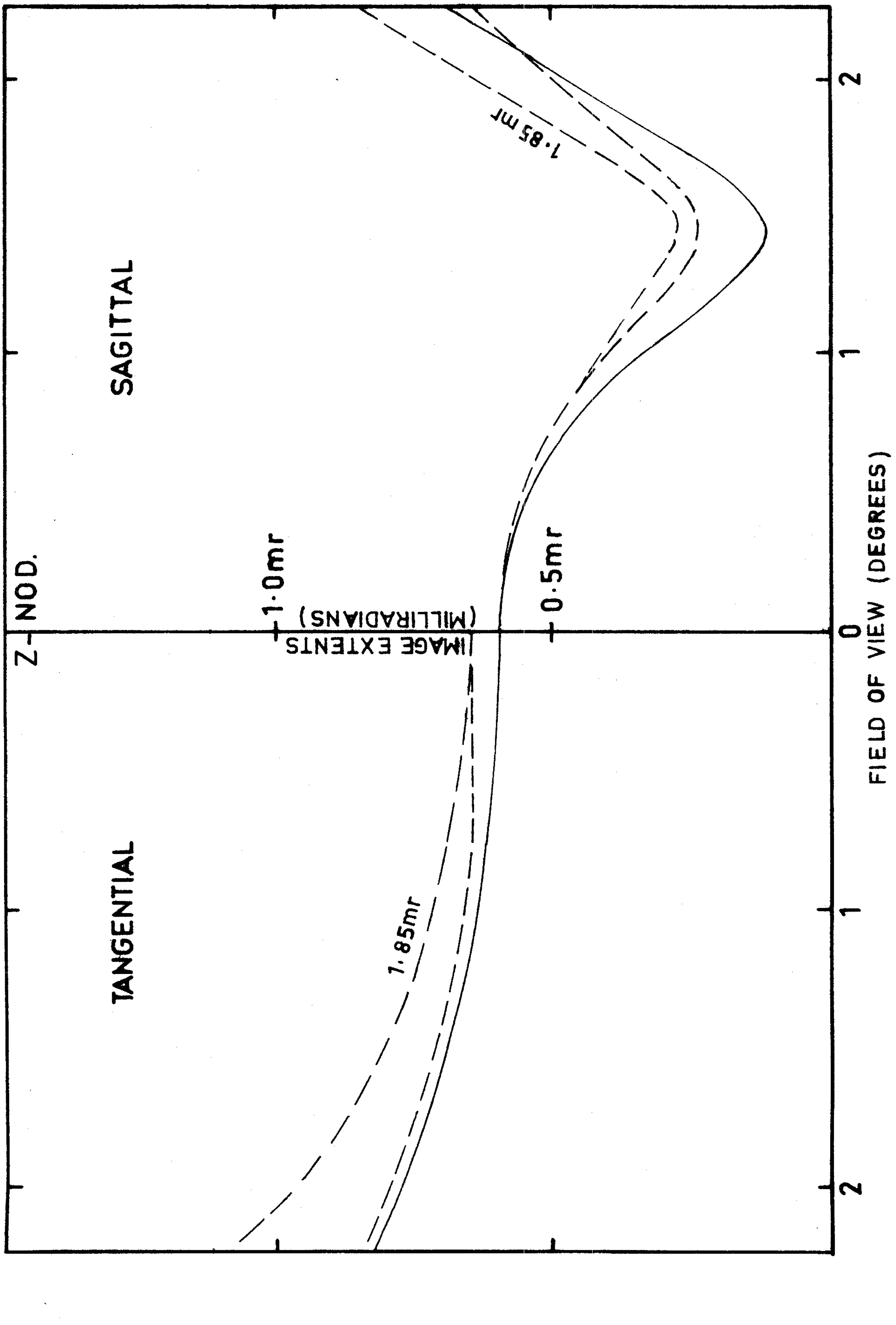

Figure 6. Image extents vs field angle for optimum focus (Z nod)

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